

Far-Infrared Spectral Line Studies of the Epoch of Reionization

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Existing cosmological observations show that the reionization history of the universe at $z > 6$ is both complex and inhomogeneous. All-sky CMB polarization measurements provide the integrated optical depth to reionization. A detailed measurement of the reionization history may come over the next decade with 21-cm HI radio interferometers, provided that they are able to remove the foregrounds down to a sub-hundredth percent level. Deep sky surveys, especially those that employ gravitational lensing as a tool, are now efficient at finding Lyman drop-out galaxies at $z > 7$, though with a large systematic uncertainty on the redshift due to degeneracies between Lyman drop-out and dusty galaxy SED templates. During the next decade the study of reionization will likely move from studying galaxies during reionization from $z = 6$ to 9 to understanding primeval stars and galaxies at $z > 10$.

In the JWST era current studies that focus on the rest-frame UV and optical lines to study the ISM and gas-phase metallicities of galaxies at $z \sim 1$ to 2 will quickly extend to z of 6. In the post-JWST era a far-infrared space telescope with a factor of 10 sensitivity improvement over SPICA will enable studies on the gas properties, AGN activity and star-formation within galaxies at $z = 6$ to 15, in addition to a large list of sciences at $z < 6$. This redshift range is especially important for our understanding of the cosmic origins, formation of first stars, galaxies and blackholes, and the onset of large-scale structure we see today. The community is already struggling with many scientific issues during this epoch. For example, an outstanding problem involves the growth of supermassive blackholes and the presence of billion to ten billion solar masses backholes at $z > 6$ at an age of 600-800 Myr after the Big Bang. One possibility to grow such high masses is seed blackholes associated with massive PopIII stars. Could we directly observe the formation of such massive stars at $z \sim 12$ to 15? And could we study the blackhole activity in galaxies at $z \sim 7$ to 10 as these blackholes grow in mass rapidly to values measured at $z \sim 6$?

To aid study of reionization 20 to 600 μm spectroscopic observations can: (a) disentangle the complex conditions in the ISM of $z = 6$ to 15 galaxies by measuring the gas densities and excitation, and the prevalence of shock heating; (b) compare the conditions of the ISM in high-redshift galaxies with local galaxies to address whether faint dwarf galaxies found at low-redshifts are analogues of galaxies during reionization; (c) use spectral line diagnostics to study AGN or star-formation regulated actively within first galaxies, including the formation of first massive blackholes; and (d) detect, measure, and map out molecular hydrogen rotational line emission from primordial cooling halos that are the formation sites of first stars and galaxies at $z > 10$.

The role of far-infrared spectral capabilities will allow diagnostic studies and ways to establish the role of feedback, radiation, and AGNs, among many others, in regulating star-formation in reionization era galaxies. For example, [OIV]26 and Ne[V]14.3 are high-ionization lines that are enhanced in AGN environments and far-IR diagnostics such as [OIV]26/[SIII]33 or [NeV]14.3/[NeIII]15.6 ratios provide a direct measure of the AGN fraction to galaxy luminosity, even when there is significant dust extinction. Such diagnostics then allow a way to distinguish galaxies at $z > 8$ that harbor AGNs and are likely to grow

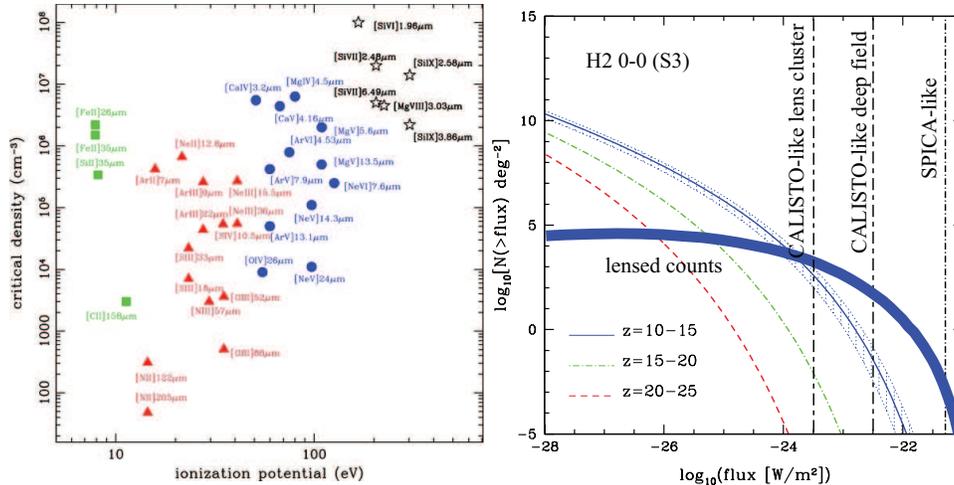


Figure 1: *Left panel:* Density-ionization diagram (Spinoglio et al. 2009) for far-IR spectra lines. Color coding shows lines separated to different conditions and radiation fields, such as stellar/HII regions or AGNs. *Right panel:* H₂ 0-0 S(3) cumulative number counts as a function of the flux density (Gong et al. 2012). In addition to intrinsic counts, we also show the gravitationally lensed counts at $z > 10$ by foreground galaxies. While SPICA or SPICA-like mission will not have the sensitivity to detect molecular hydrogen in mini-halos at the onset and during reionization, a far-infrared mission with at least a factor of 10 sensitivity improvement over SPICA, such as CALISTO, will be necessary to detect many of the important molecular hydrogen lines in the rest-frame mid-infrared wavelengths. This will require a deep 1 deg² survey over 2000 hrs. Another factor if ten depth can be achieved, on average, lensing cluster survey, similar to Hubble Frontiers Fields.

to optically luminous quasars detected with wide sky surveys such as SDSS. The mid-IR to far-IR spectral region provides both the depth and the range to initiate a wide array of studies that are still limited to lack of developments in the observational capabilities.

Moving to the highest redshifts molecular hydrogen is now understood to be the main coolant of primordial gas leading to the formation of very first stars and galaxies. It is also the most abundant molecule in the universe. There is no other signal from primordial gas cooling at the earliest epochs in either the low-frequency 21-cm background or any other cosmological probe that the community has considered. **Molecular hydrogen cooling in primordial dark matter halos will then likely the only tracer to study the transition from dark ages at $z > 20$, when no luminous sources exist, to reionization at $z < 10$.** At a metallicity $Z \sim 10^{-3.5} Z_{\odot}$ gas cooling will transit from H₂ to fine-structure lines. At $z < 8$, when primordial molecular hydrogen is easily destroyed by UV radiation, the prevalence of shocks in the ISM may provide ways to form a second and later generations of molecular hydrogen. The rotational lines of molecular hydrogen span across a decade of wavelength from 2 to 20 μm . JWST will study molecular hydrogen out to z of 1 and SPICA may be able to study them to $z \sim 3$ to 4, but at $z > 6$ SPICA does not have the required sensitivity (Fig 1 right panel).

Even if not individually detected, a far-IR survey telescope will use intensity fluctuations, similar to power spectra in CMB and Cosmic Infrared Background but in 3D due to spectral line redshift mapping, to study the spatial distribution of H₂. This intensity mapping technique also relies on a cross-correlation with a second line of H₂ from the same redshift interval to minimize foreground line contamination. The requirements for $z \sim 6$ far-IR fine-structure and $z > 10$ H₂ mapping of primeval cooling halos are 20 to 600 μm spectral coverage and a noise level below 10^{-22} W/m² in a deep 1000 to 2000 hour integration over a sq. degree area. CALISTO is one step in this direction.